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Letter

Efficient Single Image Stripe Nonuniformity Correction Method for Infrared Focal Plane Arrays

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We present a novel, stripe nonuniformity correction algorithm for infrared focal plane arrays. This method relies on the separation of nonuniformity and true scene, and the nonuniformity correction parameter is obtained by traversing the error function of two adjacent columns' pixels in local template window. Based on the succession of two adjacent columns' correlation, the stripe nonuniformity correction can be achieved in a single frame. Experimental results, to illustrate the performance of the method, include the use of infrared image sequences with simulated nonuniformity and a diverse set of real IR imagery.

Keywords: infrared focal plane arrays (IRFPA), stripe nonuniformity correction, error function, local template window, succession

IR detectors are widely used in a variety of applications such as defense, surveillance, remote sensing, astronomy, and so on. Usually, the infrared imaging sensors are based on the IR focal plane arrays (IRFPA) technology.[1] However, it is well known that nonuniformity in IR imaging sensors, which is due to pixel-to-pixel variation in the detectors' responses, can considerably degrade the quality of IR images since it results in a fixed-pattern-noise (FPN) that is superimposed on the true image. Stripe nonuniformity as a special fixed pattern noise, is particularly prominent in line IRFPA and un-cooled starring IRFPA, and it has the column stripe nonuniformity commonly. Figure 1 shows an image with true stripe nonuniformity.

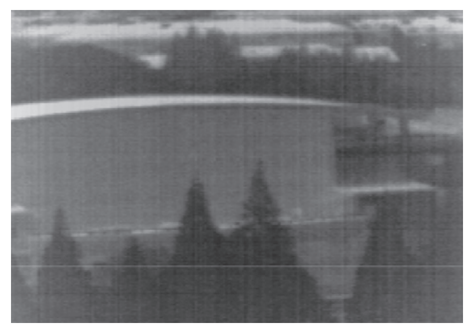

Fig. 1. Image of an un-cooled staring IR-FPA with stripe nonuniformity.

Nonuniformity correction (NUC) techniques have been developed and implemented to perform the necessary calibration for all IR imaging applications. These correction techniques can be classified into two categories: 1) reference-based correction using calibrated images on startup, and the problems have been well-documented in the literature,[3] 2) scene-based NUC has been developed to overcome these drawbacks by continuously correcting FPA nonuniformity without reset.[1–3)]

Numerous NUC techniques have been developed over the years. There are two main categories of scene-based NUC: Statistical methods[1–3,5,6] and registration methods.[4] Scribner *et al.*[5] developed a least mean square based NUC technique that resembles adaptive temporal high-pass filtering of frames. Hardie *et al.*[4] considered the estimation of global motion and developed a registration-based approach to NUC [motion compensated average (MCA) algorithm]. These approaches are proposed for common nonuniformity correction, and stripe nonuniformity should have special methods. Yang *et al.*[8] proposed a method using wavelet analysis. Qian *et al.*[9] developed a de-striping algorithm, by taking into account the edge of the scene, which is based on gray-scale co-occurrence matrix theory and the optimization theory. Although the stripe nonuniformity parameter is obtained in a single frame, it easily has residual low frequency noise.

The line IRFPA and the un-cooled staring IRFPA have similar mechanisms of the stripe nonuniformity. Nowadays, all IRFPA readout circuits are designed based on the CMOS structure. The CMOS has many amplifiers, and one pixel corresponds to one amplifier. For cost consideration in IRFPA, mostly each column's pixels share one amplifier, and one column corresponds to one amplifier. Thus, the column stripe nonuniformity is obtained. Aiming at the simple and effective stripe NUC method, in this Letter we propose a novel stripe nonuniformity correction algorithm for IRFPA. Based on the separation of nonuniformity and true scene, the nonuniformity correction parameter is obtained by traversing the error function of two adjacent column pixels in local template window. Because of the succession of two adjacent columns' correlation, the stripe nonuniformity correction can be achieved in single frame.

At any given frame n ($n = 1, 2, 3, \ldots$), the FPN generative model for each (i, j)th detector in the FPA is often described by a linear relationship between the incoming irradiance

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and the output value, and the observed output pixel value $Y_{i,j}(n)$ is given by

$$Y_{i,j}(n) = G_{i,j}(n) \cdot X_{i,j}(n) + O_{i,j}(n) \qquad (i \in [1, M]; j \in [1, N]), \tag{1}$$

where the variable $G_{i,j}(n)$ represents the gain of the (i,j)th detector and $O_{i,j}(n)$ is the offset of detector. $X_{i,j}(n)$ stands for the real incident infrared photon flux collected by the respective detector. M and N are the row and column parameters associated to the FPA, respectively.

Let us assume that the gains and biases drift very slowly in time and are almost fixed with respect to frame index. Without loss of generality, the gain is assumed uniform across all detectors with a value of unity. Considering the particularity of stripe nonuniformity, they have the same offset in one column. The observed pixel value $Y_{i,j}(n)$ is reduced to

$$Y_{i,j}(n) = X_{i,j}(n) + O_j(n). \tag{2}$$

Nonuniformity correction is performed by applying a linear mapping (a function between two vector spaces that preserves the operations of vector addition and scalar multiplication) to the observed pixel values to provide an estimation of the true scene value so that the detectors appear to be performing uniformly. This correction is given by

$$X_{i,j}(n) = Y_{i,j}(n) + b_j(n), \tag{3}$$

where $b_j(n)$ is the estimation of offset parameter. Therefore, once ideal estimates of $b_j(n)$ can be obtained, the nonuniformity correction could be realized through eq. (3). From the discussion above, here we define the error function between two adjacent columns:

$$E_{i,j}(n) = Y_{i,j}(n) - Y_{i,j-1}(n). \tag{4}$$

The error function $E_{i,j}(n)$ is obtained by subtracting the forward observed pixel value $Y_{i,j-1}(n)$ from current observed pixel value $Y_{i,j}(n)$. To estimate the difference between two adjacent columns' nonuniformity, the standard deviation is obtained by calculating the $E_{i,j}(n)$, which makes use of local template window. Therefore, we define the standard deviation function

$$S_{i,j}(n) = \operatorname{std} \Pi_O[E_{i,j}(n)] = \sqrt{\frac{\sum_{p=i-w}^{i+w} \left\{ E_{p,j}(n) - \left[\sum_{q=i-w}^{i+w} E_{q,j} \Big/ (2w+1) \right] \right\}^2}{2w+1}} \qquad i \in [w, M-w]. \tag{5}$$

For $(2w+1)$ is the local template window. Note that in eq. (5), the standard deviation is accurately estimated. It is a direct indicator on whether the detectors of two adjacent columns in the window fall in the flat region. In dynamic regions with high spatial standard variance, the error function $E_{i,j}(n)$ is more likely composed of scene value. On the other hand, smaller $S_{i,j}(n)$ means that the error function $E_{i,j}(n)$ should be composed of highly correlated nonuniformity. Therefore, we calculate the minimum of the standard deviation $S_{i,j}(n)$, which is regarded as the flattest region, and it is given by

$$mS_{i,j}(n) = \min[S_{i,j}(n)], \tag{6}$$

where the symbol min denotes procedure of calculating the minimum. Then we will find the corresponding row and column coordinate of $mS_{i,j}(n)$:

$$[x\ j] = \mathit{find}[S_{i,j}(n) == mS_{i,j}(n)]. \tag{7}$$

Thus, we can calculate the mean of error function $E_{i,j}(n)$ in local template window at the coordinate $[x\ j]$. We can get the difference value of two adjacent columns:

$$\Delta b_{i,j}(n) = b_{i,j}(n) - b_{i,j-1}(n) = \frac{\sum_{k=x-w}^{x+w} E_{k,j}}{2w+1}. \tag{8}$$

For $j = 1, \ldots, N$, based on the succession of two adjacent correlation, $b_{i,j}(n)$ is obtained.

To compare the various stripe NUC algorithms, and in particular demonstrate the efficacy of the proposed algorithm, we use a set of uniform video sequence with simulated nonuniformity and an infrared video sequence with real nonuniformity.

The performance of the proposed algorithm is studied and compared with the performance of MCA and ref. 10 method by applying these algorithms to 14 bit infrared image sequences corrupted by simulated nonuniformity. The infrared sequences with artificial nonuniformity are generated from a clear 700 frame infrared video sequence, which was collected at 11 a.m. by using a 320×256 HgCdTe FPA camera operating in the 8–14 μm range and working at 50 fps (frames per second). The infrared sequence is added with artificial nonuniformity using synthetic offset with a zero-mean Gaussian distribution with standard deviation of 20 in 14 bit data. The metric used to measure the NUC performance is given by the root mean square error (RMSE), which is defined as

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{M} \sum_{j=1}^{N} [\hat{Y}(i,j) - Y(i,j)]^2}{M \times N}}, \tag{9}$$

where $Y(i,j)$ is the (i,j)th pixel's value of the true frame, while $\hat{Y}(i,j)$ is the pixel's value of the corrected frame. $M \times N$ denotes the size of image. RMSE is used to measure the overall difference between a clean reference image and its noisy nonuniformity-corrected versions.

The comparison results are displayed in Fig. 2. The size of local template window is 1×11 ($w = 5$). Figure 2 shows the images for the 150th frame. Figure 2(a) shows the raw image corrupted with simulated nonuniformity. The outputs using MCA, ref. 10 method and the proposed method are shown in Figs. 2(b)–2(d), respectively. Figure 2(e) shows the estimation offset part of nonuniformity. The relations of RMSE curves to frame numbers of three different algorithms are shown in Fig. 2(f).

The smaller the RMSE is, the better the NUC effect is. It can be observed from Fig. 2 that the proposed method has a better correction result, ant it can estimate the corrected parameter accurately. Although MCA method has a certain

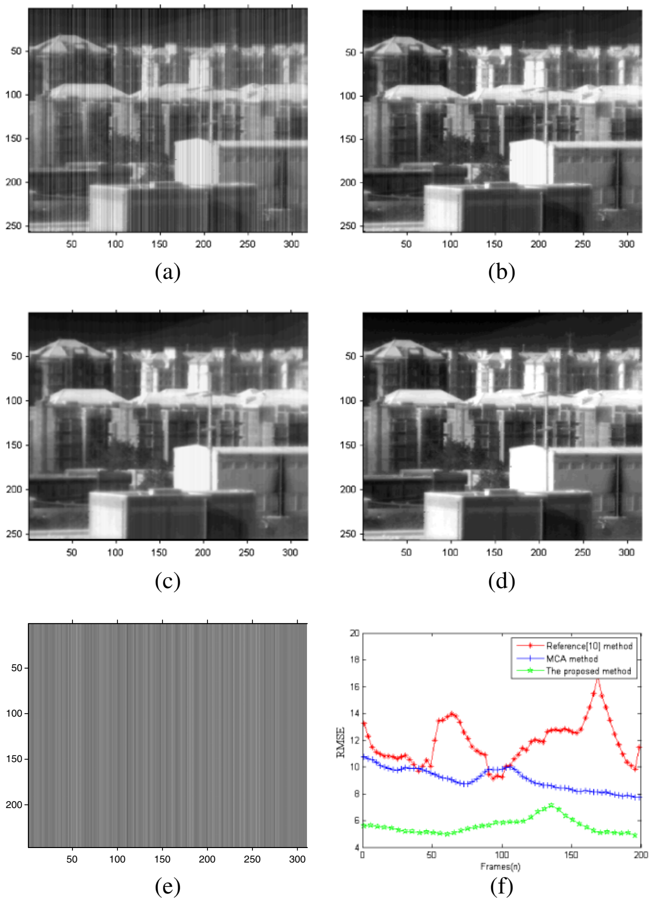

Fig. 2. (Color online) (a) Frame 150th with simulated nonuniformity. (b) Corrected with MCA method. (c) Corrected with ref. 10 method. (d) Corrected with the proposed method. (e) Estimation offset part of nonuniformity. (f) RMSE versus frame number using different methods.

effect, its RMSE is relatively high. MCA method was proposed for 2D fixed pattern noise, and it is not suitable for stripe nonuniformity correction. Reference 10 method takes into account the edge of the scene, which is based on gray-scale co-occurrence matrix theory, causing residual non-uniformity easily. With the change in scene, the correction effect will be different.

In this subsection, the algorithm put forward is applied to a set of real infrared data video sequence with nonuniformity. The set of data was collected at 11 a.m. by using a 320×240 pixels long wavelength un-cooled vanadium oxide FPA camera at 25 fps from a tall building. One sample image of the test sequence and the correction results with different methods are shown in Fig. 3.

In Fig. 3(a) we can see that the raw infrared video sequence was degraded by stripe fixed pattern noise. We compared the correction results by using the MCA method, ref. 10 method and the proposed method. It can be seen that the nonuniformity presented in the raw frame has been notably reduced by all the NUC methods. The proposed method gives the best correction result, while in both MCA method and ref. 10 methods, residual nonuniformity are detected by the naked eyes [Figs. 3(b) and 3(c)].

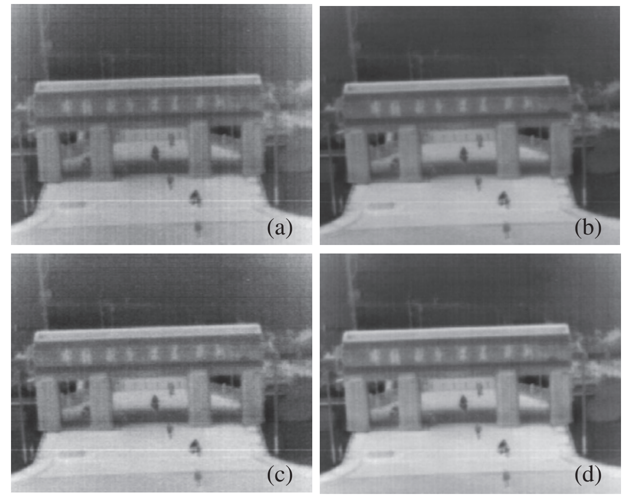

Fig. 3. (a) Sample image from the video sequence (180th frame). (b) Corrected the sample image using the MCA method. (c) Corrected the sample image using ref. 10 method. (d) Corrected the sample image using the proposed method.

In conclusion, we have presented a novel stripe non-uniformity correction method for array detectors in a single frame. The method estimates nonuniformity correction parameter by traversing the error function of two adjacent columns' pixels using local template window. The proposed algorithm has shown its superiority to ref. 10 method in that it greatly removes stripe fixed pattern noise. And the algorithm can be easily implemented in hardware for real-time application.

Acknowledgments

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